Testing Cosmological Models With A Lyα Forest Statistic: The High End Of The Optical Depth Distribution

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ABSTRACT

We pay particular attention to the high end of the Lyα optical depth distribution of a quasar spectrum. Based on the flux distribution (Miralda-Escudé et al. 1996), a simple yet seemingly cosmological model-differentiating statistic, Δ_{τ_0} — the cumulative probability of a quasar spectrum with Lyα optical depth greater than a high value τ_0 — is emphasized. It is shown that two different models — the cold dark matter model with a cosmological constant and the mixed hot and cold dark matter model, both normalized to COBE and local galaxy cluster abundance — yield quite different values of Δ_{τ_0}: 0.13 of the former versus 0.058 of the latter for $\tau_0 = 3.0$ at $z = 3$. Moreover, it is argued that Δ_{τ_0} may be fairly robust to compute theoretically because it does not seem to depend sensitively on small variations of simulations parameters such as radiation field, cooling, feedback process, radiative transfer, resolution and simulation volume within the plausible ranges of the concerned quantities. Furthermore, it is illustrated that Δ_{τ_0} can be obtained sufficiently accurately from currently available observed quasar spectra for $\tau_0 \sim 3.0 - 4.0$, when observational noise is properly taken into account. We anticipate that analyses of observations of quasar Lyα absorption spectra over a range of redshift may be able to constrain the redshift evolution of the amplitude of the density fluctuations on small-to-intermediate scales, therefore providing an independent constraint on Ω_0, $\Omega_{0,HDM}$ and Λ_0.

Subject headings: Cosmology: large-scale structure of Universe – cosmology: theory – intergalactic medium – quasars: absorption lines – hydrodynamics

1. Introduction

Any acceptable theory for growth of structure has to pass the tests imposed by observations in our local ($z = 0$) universe. Among those the most stringent is provided by observations of clusters of galaxies (Bahcall & Cen 1992; Oukbir & Blanchard 1992; Bahcall & Cen 1993; White et al. 1993; Viana & Liddle 1995; Bond & Myers 1996; Eke, Cole, & Frenk 1996; Pen 1996), simply because they probe the tail of a Gaussian (or alike) distribution, which depends extremely strongly on some otherwise fairly stable quantities such as the rms of density fluctuation amplitude. In addition, a model has to match COBE observations of the universe at the epoch of recombination (Smoot et al. 1992). The combination of these two relatively fixed points defines the shape and amplitude of the assumed power spectrum, thus significantly limiting the allowable parameter space for the Gaussian family of the cold dark matter cosmological models; one is essentially left undecided how to adjust the following three parameters: n, Λ_0 or $\Omega_{0,hot}$, where n is the primordial power spectrum index, Λ_0 the current cosmological constant and $\Omega_{0,hot}$ density parameter of the hot dark matter. Critical differentiators are likely to come from areas which are as far removed as possible from both COBE epoch (on large scales) and our local vantage point (on scales of $\sim 8h^{-1}$Mpc).

In the intervening redshifts, among those accessible to current observations, the Lyα forest observed in spectra of high redshift quasars (e.g., Carswell et al. 1991; Rauch et al. 1993; Petitjean et al. 1993; Schneider et al. 1993; Cristiani et al. 1995; Hu et al. 1995; Tytler et al. 1995; Lanzetta et al. 1995; Bahcall et al. 1996) provides possibly the single richest set of information about the structure of the universe at low-to-moderate redshift. Furthermore, each line of sight to a distant quasar indiscriminately samples the distribution of neutral hydrogen gas (hence total gas) over a wide redshift range ($z \sim 0-5$) in a *random* fashion (i.e., a quasar and foreground absorbing material are unrelated); thus, the Lyα

forest constitutes perhaps the *fairest* sample of the cosmic structure in its observed redshift range.

The new *ab initio* modeling of Lyα clouds by following the gravitational growth of baryonic density fluctuations on small-to-intermediate scales ($\sim$ 100kpc to several Mpc in comoving length units) produced a remarkably successful account of the many observed properties of Lyα clouds (Cen et al. 1994; Zhang et al. 1995; Hernquist et al. 1996; Miralda-Escudé et al. 1996). However, at first sight it appears that three *different* cosmological models — a CDM+Λ model (Hubble constant $H_o = 65$km s^{-1} Mpc^{-1}, $\Omega_{0,CDM} = 0.3645$, $\Lambda_0 = 0.6$, $\Omega_{0,b} = 0.0355$, $\sigma_8 = 0.79$; Cen et al. 1994), a biased critical density CDM model ($H_o = 50$km s^{-1} Mpc^{-1}, $\Omega_{0,CDM} = 0.95$, $\Omega_{0,b} = 0.05$, $\sigma_8 = 0.70$; Hernquist et al. 1996), and a high amplitude critical density CDM model ($H_o = 70$km s^{-1} Mpc^{-1}, $\Omega_{0,CDM} = 0.96$, $\Omega_{0,b} = 0.04$, $\sigma_8 = 1.00$; Zhang et al. 1995) — all approximately fit observations, gauged by column density distribution, Doppler width b distribution, etc. While the overall agreement between models and observations is encouraging from an astrophysicist's point of view because it implies that the physical environment produced by the hydrocodes of widely distributed photoionized gas does correspond to the real world, it seems that more sensitive tests are demanded from a cosmologist's point of view in order to test models. In this *Letter* we show that a statistic based on the Lyα flux distribution may serve as a potentially strong discriminator between cosmological models. We argue that, while the column density distribution is useful in providing information about the Lyα clouds, it requires post-observation fitting procedures such as line profile fitting and line deblending, and it consequently superimposed by additional uncertainties related to the procedures themselves. Naively, it may seem that measures based on the flux (or optical depth) distribution may be redundant given that we already have the traditional column density distribution. But we note that in complex multivariate problems (Kendall 1980) such as that of the Lyα forest it should not be taken for granted that a one-to-one correspondence

or correlation between the two exists. In other words, two different flux distributions may yield a similar column density distribution considering the many factors involved, including real space clustering, thermal broadening, peculiar velocity effect and line profile fitting. Therefore, it may be profitable to deal directly with the flux distribution.

2. A Statistic: Fraction Of A Spectrum With $\tau_{\rm Ly}\alpha > \tau_0$

We use two of the current popular models — the cold dark matter model with a cosmological constant (ΛCDM) and the mixed hot and cold dark matter model (MDM) — to demonstrate the applicability of the statistic.

We begin by showing the variance of the density fluctuations ($\sigma \equiv \sqrt{\langle\delta^2\rangle - 1}$, where $\delta \equiv \delta\rho/\langle\rho\rangle$ calculated using linear theory) as a function of the comoving radius of a sphere in the ΛCDM model (solid curve) and the MDM model (dashed curve) at $z = 3$ in Figure 1. Both the ΛCDM model (Hubble constant $H_o = 65$km s^{-1} Mpc^{-1}, $\Omega_{0,CDM} = 0.3645$, $\Lambda_0 = 0.6$, $\Omega_{0,b} = 0.0355$, $\sigma_8 = 0.79$) and the MDM model ($H_o = 50$km s^{-1} Mpc^{-1}, $\Omega_{0,CDM} = 0.74$, $\Omega_{0,HDM} = 0.2$, $\Omega_{0,b} = 0.06$, $\sigma_8 = 0.70$; Ma 1996) are normalized to both COBE on large scales and local galaxy cluster abundance (on scales of $\sim 8h^{-1}$Mpc comoving). Both models involve a slight tilt of the spectrum (plus some small gravitational wave contribution to the temperature fluctuations on large scales in the ΛCDM model) in order to achieve the indicated σ_8 values. We see a somewhat *modest* difference in the amplitude of density fluctuations in the two models. The density fluctuations are larger in the ΛCDM than in the MDM model by (26%, 33%) on scales of ($0.1h^{-1}$Mpc, $1.0h^{-1}$Mpc), respectively.

Focusing on the high end of the optical depth distribution the following statistic is examined for the purpose of testing cosmological models — the fraction of pixels in a quasar

spectrum with Lyα optical depth greater than τ_0:

$$\Delta_{\tau_0} \equiv P(>\tau_0), \tag{1}$$

where $P(>\tau_0)$ is the cumulative distribution of Lyα optical depth. In Figure 2, we show the results of the ΛCDM model (thick solid curve) and the MDM model (thick dashed curve) obtained from detailed synthetic Lyα spectra (Miralda-Escudé et al. 1996). A sampling bin of 2.0km s^{-1} is used and the spectrum is degraded by a point spread function with a 6.0km s^{-1} FWHM. Note that noise is *not* added for the two thick curves in Figure 2. The boxsize, resolution and physics input of the two simulations are identical (for details of the ΛCDM model see Miralda-Escudé et al. 1996). The differences between the two model simulations are: 1) different input power spectra, 2) different background models and, 3) there is one additional (hot) dark matter species in the MDM simulation. Ionization equilibrium between photoionization and recombination is assumed. We require that the average flux decrement in each model, $\langle D\rangle = 1 - \langle \exp^{-\tau_{\mathrm{Ly}\alpha}}\rangle$, be equal to the observed value, $\langle D\rangle_{obs} = 0.36$ at $z = 3$ (Press, Rybicki, & Schneider 1993). This is achieved by adjusting the following parameter: $\mu \equiv \frac{(\Omega_{0,b}/0.015h^{-2})}{(h\ j_H/10^{-12}\mathrm{sec}^{-1})^{1/2}}$, where h is Hubble constant in units of 100km/s/Mpc, $\Omega_{0,b}$ is the mean baryonic density and j_H is the hydrogen photonization rate. This normalization procedure for the flux distribution is *necessary* in order to fix its overall amplitude, due to the large uncertainties of the observed values of $\Omega_{0,b}$ and j_H. The fitted values of μ are 1.90 and 1.47, respectively, for the ΛCDM and the MDM models (note that the value of μ for the MDM model is obtained after the temperature of the intergalactic medium in the model is raised; see below).

Although the ΛCDM model yields temperature of the clouds consistent with observations, as indicated by the b parameter distribution (Miralda-Escudé et al. 1996), it is found that the mean temperature of the intergalactic medium in the MDM model at $z = 3$ is unrealistically low with $\langle T\rangle \sim 100$ Kelvin (compared to $\langle T\rangle \sim 15,000$ Kelvin

in the ΛCDM). The reason is that our self-consistent treatment of structure formation (star/galaxy formation) and ionizing radiation field does not produce sufficient photo-ionization/photo-heating of the intergalactic medium due to the very small fraction of baryons which have collapsed to form stars or quasars in the MDM model by $z = 3$ [for details of our treatment of atomic processes, radiation, and galaxy formation see Cen (1992) and Cen & Ostriker (1993)]. It would be meaningless had we generated the Lyα spectrum for the MDM model using such low temperature. Instead, we uniformly raise the gas temperature in the MDM model to 2×10^4 Kelvin (but retain other properties of the gas including density and velocity), and then generate the Lyα spectrum with thermal broadening effect of the gas of the putative high temperature. To test the sensitivity of the results on the artificial temperature adjustment in the MDM model, we also compute the results by raising the temperature to 4×10^4 Kelvin and 1×10^4 Kelvin, respectively. We find that at $\tau_0 = (3.0, 4.0, 5.0)$, the results are $\Delta_{\tau_0} = (0.054, 0.039, 0.029)$, $(0.058, 0.041, 0.032)$ and $(0.071, 0.051, 0.041)$ for three cases with $T = 4 \times 10^4$, $T = 2 \times 10^4$, $T = 1 \times 10^4$ Kelvin, respectively. One more experiment is made for the MDM model: instead of setting the temperature uniformly to 2×10^4 Kelvin, 2×10^4 Kelvin is *added* uniformly to the temperature of each cell, and we find the results of Δ_{τ_0} for the two cases are indistinguishable within the quoted digits, at all three τ_0's. It seems that the results depend only weakly on the temperature within the reasonable range, with the trend that higher temperatures yield lower fractions of pixels with high optical depth.

We find that $\Delta_{\tau_0}(\Lambda\mathrm{CDM}) = (0.12, 0.10, 0.088)$ and $\Delta_{\tau_0}(\mathrm{MDM}) = (0.058, 0.040, 0.031)$, at $\tau_0 = (3.0, 4.0, 5.0)$, respectively, i.e., a difference between the two models by a factor of $(2.1, 2.5, 2.8)$ at the three τ_0's. It is likely that the high end of the Lyα optical depth distribution in the MDM model (thick dashed curve) would be further reduced, had we run the simulation with sufficient (i.e. realistic) photo-ionization/photo-heating, since reduced cooling and increased thermal pressure would result in less condensation of dense regions

responsible for high Lyα optical depth considered here. The countervailing effect is that the current MDM simulation may have overcooled the dense clouds, making them much smaller thus much less capable of intercepting QSO lines of sight. However, examinations of the cloud sizes and densities in the dense regions as well as the found trend of higher temperatures yielding lower high optical depth fraction (see the preceding paragraph) indicate that this effect is unimportant for the MDM model; there do not seem to exist superdense clouds in the MDM model. In short, we anticipate that a more realistic MDM simulation with higher photoionization field would produce even smaller τ_0 than that of the current MDM simulation.

It is clear from Figure 2 that the higher the τ_0, the more model-differentiating power Δ_{τ_0} possesses. However, detecting high τ_0 is difficult due to noise and telescope systematics. To see how noise affects the statistic, we generated synthetic spectra with noise added in the following way. By definition, the signal to noise ratio at the continuum is S/N$= \frac{N_{src}}{\sqrt{N_{src}+N_{noise}}}$, where N_{src}, N_{noise} and S/N are the number of source photons at the continuum, the number of noise photons and the signal to noise ratio, respectively, per frequency pixel. Thus, given S/N and N_{noise}, we can obtain N_{src}. To simplify the illustration (without loss of generality) we assume that N_{noise} is dominated by the detector readout noise. This is a good approximation only for a bright quasar where the number of sky photons are small (due to a shorter exposure time) compared to the readout noise of, say, a CCD detector. For example, the gain of the HIRES CCD detector on the Keck telescope is 6.1 electrons, so the number of photons due to the CCD readout noise integrated over 5 spatial pixels (for each frequency bin) is $N_{CCD} = 5 \times 6.1^2 = 186$. For a $V = 16.5$ mag quasar at 5000A with 1-hr integration time, about 4 photons from the sky per spatial pixel, giving a total count of sky photons per frequency pixel (integrated over the 5 spatial pixels) of only 20 photons (see, e.g., Hu et al. 1995). A frequency pixel in the simulated noise-free spectrum with flux f contains fN_{src} photons. When noise is added, the "observed" number of photons

(subtracted by the known CCD noise) in the pixel will be $Poisson(fN_{src}+N_{CCD})-N_{CCD}$, where $Poisson(X)$ means a Poisson distributed random number with the mean equal to X. The resultant distributions $[P(\tau)]$ are also shown in Figure 2 for three continuum signal to noise ratios of S/N= $(50, 100, 150)$ for each model (thin solid curves for the ΛCDM model and thin dashed curves for the MDM model). The 6σ statistical errorbars are also shown for the case with S/N= 100 (other cases have comparable errorbars but are not shown to maintain the readability of the plot), assuming a quasar absorption spectrum coverage of unit redshift range about z=3 with a sampling bin of 2km s^{-1}. The N_{CCD} value of the HIRES CCD detector is adopted in the calculation. We see that three values of S/N= $(50, 100, 150)$ are able to preserve the differences between the two models up to $\tau_{\mathrm{Ly}\alpha} \sim (2.5, 3.0, 3.5)$, respectively. Another complication, telescope systematics, may cause further difficulties. Nevertheless, it seems that Δ_{τ_0} for $\tau_0 = 3.0$ can be fairly accurately obtained with a high statistical accuracy in good Keck spectra [e.g., Womble, Sargent, & Lyons (1995) achieved a typical signal to noise ratio of 150 per resolution element using the HIRES spectrograph on the Keck telescope].

A preliminary comparison of the simulation results using Δ_{τ_0} with observations (Rauch et al. 1997, Figure 1) at $\tau_0 = 3.0$ at $z \sim 3$ appears that the result of the ΛCDM model matches the observed value well (~ 0.10 computed versus ~ 0.11 observed), while the MDM model seems to predict a value (0.04) lower than observed.

3. Discussion and Conclusions

This study illustrates that high quality quasar Lyα absorption spectra are potentially useful to discriminate between cosmological models. It is demonstrated that the Δ_{τ_0} statistic — the cumulative probability of a spectrum with Lyα optical depth greater than a high value τ_0 ($\sim 3.0 - 5.0$) — serves as an amplifier of the differences between models. We

show that a modest difference ($\sim 25 - 30\%$) in the mean amplitudes translates into a large difference in the two Δ_{τ_0}'s (by a factor larger than 2.0 for $\tau_0 > 3.0$) between the ΛCDM model and the MDM model at $z = 3$. Moreover, the value of Δ_{τ_0} is at the level of 0.01 to 0.1, i.e., the relevant regions with $\tau_{\mathrm{Ly}\alpha} > \tau_0$ cover a sizable portion of a quasar spectrum. Therefore, one is *not* dealing with small number statistics, ensuring that Δ_{τ_0} is a potentially accurately determinable statistic statistically. The statistic is also *simple* in that it does not involve complicated procedures such as line profile fitting, and hence can be directly applied to the observed flux distribution.

In addition to the need of a high signal-to-noise ratio (S/N$\geq$ 100 for $\tau_0 \geq 3.0$), it is essential that telescope systematics be understood and scattered noise photons be minimized, which may push one to focus on the brightest quasars at this time. Furthermore, it is required that the spectroscopic resolution be sufficiently high so that Lyα optical depth can be reliably extracted from the observed flux. The latter requirement is equivalent to having a FWHM less the Doppler width, which seems readily satisfied with current observations. Finally, we note that a stable normalization procedure for the overall flux distribution is necessary due to large uncertainties in $\Omega_{0,b}$ and j_H. We adopt $\langle D\rangle_{obs}$ as a normalization parameter in this work. The primary difficulty in fixing $\langle D\rangle_{obs}$ is to determine the continuum, which is fairly obscured by heavy absorption at high redshift (compare, e.g., Zuo & Lu 1993 and Press, Rybicki, & Schneider 1993 to see the situation); the situation is better at lower redshift.

It is equally essential to determine the robustness of the prediction of a theoretical model for the proposed statistic. This may only be made definitive by performing many simulations with varying input parameters including the ionization radiation field, baryonic density, feedback processes, simulation resolution and simulation volume (boxsize). It is expected, however, that all these effects may not change results significantly. Let us

take an example to illustrate this conjecture. A Lyα cloud with a column density of $N = 1 \times 10^{14}\mathrm{cm}^{-2}$ and a Doppler width $b = 25\mathrm{km\ s}^{-1}$ has a central Lyα optical depth of ~ 3.0. Since these clouds are not cooling efficiently (cooling time is longer than the Hubble time), cooling effects are likely to be small, implying that changing radiation field or baryonic density would have a small dynamic effect within plausible ranges. For the same reason, these clouds are not effective in forming stars, therefore feedback effect may be small (which, if any, may be due to nearby star forming regions, which may be much rarer.) These clouds are also found to be relatively large and well resolved in our current simulations, but small compared to the simulation boxsize, so an increase of simulation resolution or boxsize would not affect the statistic substantially. Lastly, we note that, since the relevant regions are optically thin to Lyman limit photons, self-shielding effects are likely to be unimportant. So it appears that Δ_{τ_0} is a relatively *easy* statistic to determine theoretically.

We anticipate that the evolution of different models may be quite different, due to the dependence of the growth of density fluctuations on Ω_0, $\Omega_{0,HDM}$ and Λ_0 (Peebles 1980), possibly coupled with other nonlinear, redshift dependent thermal/dynamical effects. The redshift evolution of Δ_{τ_0}, computable with both observations and simulations of different models, may be potentially revealing. It is conceivable that we can constrain the amplitude of density fluctuations on small-to-intermediate scales as a function of redshift using observations of Lyα clouds, thus possibly constrain Ω_0, $\Omega_{0,HDM}$ and Λ_0.

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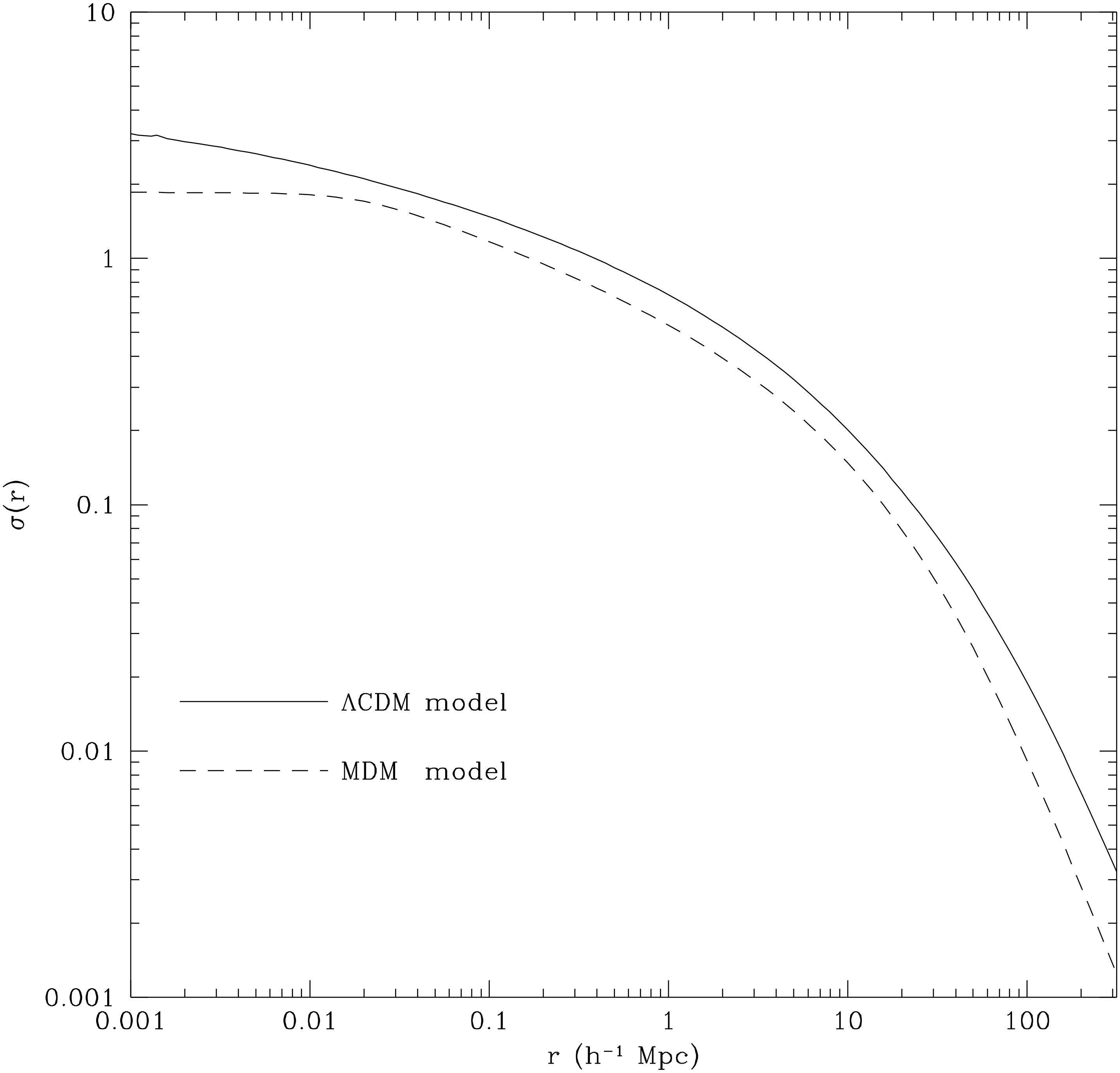
Fig. 1.— shows the variance of density fluctuations as a function of scale (comoving) in the ΛCDM model (solid curve) and the MDM model (dashed curve) at redshift $z = 3$.

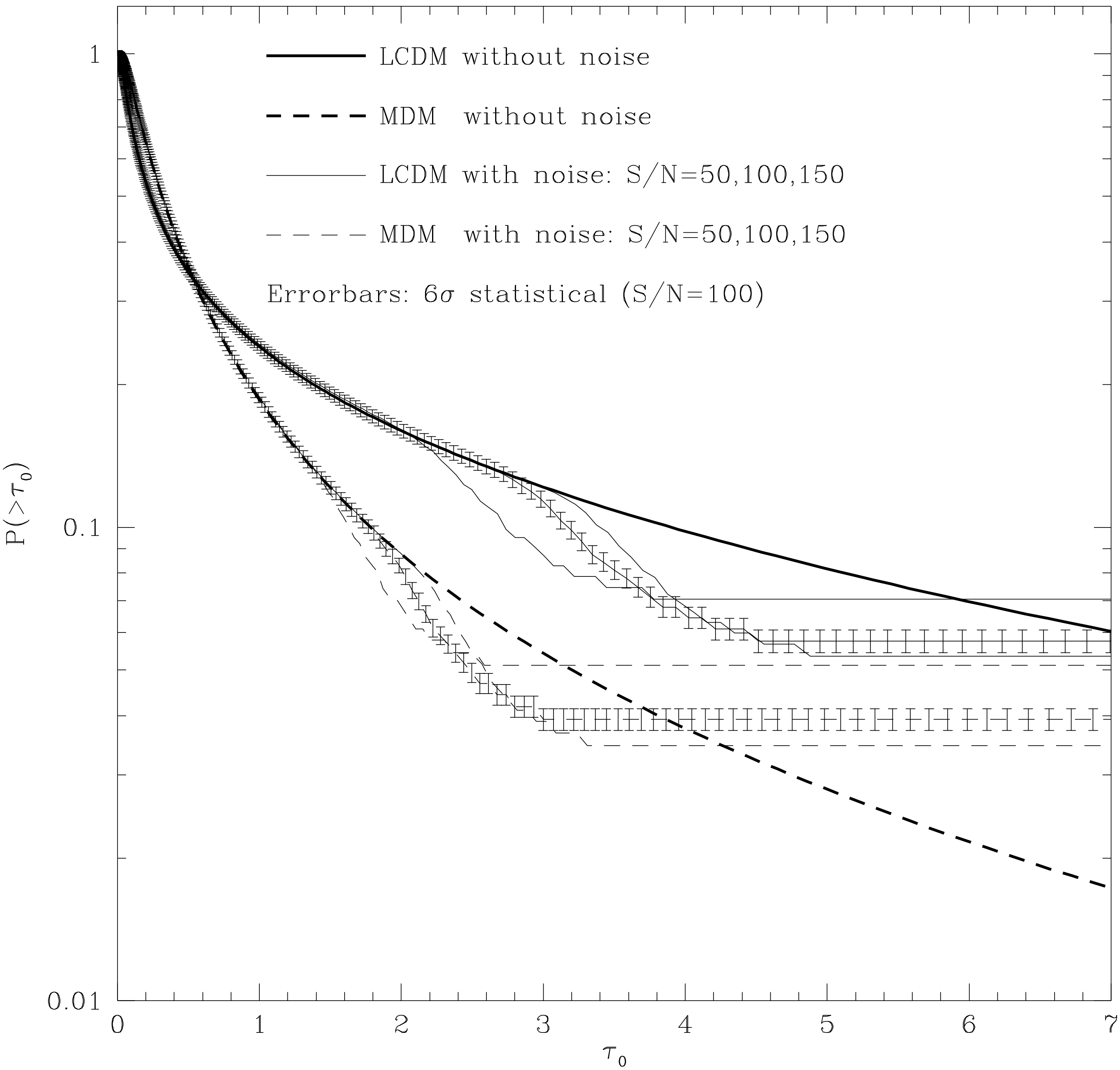
Fig. 2.— shows the (cumulative) distributions of the optical depth in the ΛCDM model (solid curve) and the MDM model (dashed curve) at $z = 3$. The two thick curves do not include observational noise. The three thin solid curves include observational noise with signal to noise ratio at the continuum being $(50, 100, 150)$, respectively, for the ΛCDM model. The three thin dashed curves show the counterparts for the MDM model. The 6σ statistical errorbars are also shown for the case with S/N= 100 (other cases have comparable errorbars but are not shown for the sake of readabilty of the figure), assuming that a quasar absorption spectrum coverage of unit redshift range about z=3 with a sampling bin of 2km s^{-1}. The value of $N_{CCD} = 181$ of the HIRES CCD detector is adopted in the calculation of noise added spectra (noise due to sky photons is ignored). All curves are normalized to yield the observed average decrement at z=3 of $\langle D\rangle_{obs} = 0.36$ (Press, Rybicki, & Schneider 1993).

Figure 1



10
1
0.1
0.01
0.001
σ(r)
0.001
0.01
0.1
1
10
100
r (h⁻¹ Mpc)
ΛCDM model
MDM model

Figure 2



LCDM without noise
MDM without noise
LCDM with noise: S/N=50,100,150
MDM with noise: S/N=50,100,150
Errorbars: 6σ statistical (S/N=100)
P(>τ0)
1
0.1
0.01
0
1
2
3
4
5
6
7
τ0